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The Effect of TiC Coated Balls and Stress on the Lubricant Lifetime of a Synthetic Hydrocarbon (Pennzane 2001A) Using a Vacuum Spiral Orbit Tribometer

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ABSTRACT

A vacuum spiral orbit rolling contact tribometer was used to determine effect of varying mean Hertzian stress (1.0, 1.5, 2.0 GPa) and the use of 440C and TiC coated 440C balls on lubricant lifetime of a synthetic hydrocarbon (Pennzane 2001A) on 440C stainless steel. Conditions included 210 RPM, ~50 µg lubricant, an initial vacuum $<1.3 \times 10^{-6}$ Pa, and room temperature (~23°C). Increasing the mean Hertzian stress resulted in an exponential decrease in lubricant lifetime for both material combinations. Substituting a TiC coated 440C ball showed no increase in lifetime over the 440C ball. The decreasing lifetime with increasing stress level correlated well with energy dissipation calculations.

INTRODUCTION

The materials revolution from improved steels and advanced ceramics had made its way into ball bearing technology years ago. Today, much is known of the advantage of hybrid bearings (steel raceways and ceramic balls) and they are used in many applications such as in the machine tool industry and next generation, high speed, momentum wheel applications.

Pseudo-hybrid bearings (steel raceways and TiC coated steel balls) are state-of-the-art in many aerospace applications such as inertial navigation instruments and space mechanisms requiring high precision pointing accuracy and low torque noise.

TiC coated balls have several important features that make them a favorable compromise to both conventional and hybrid bearings. TiC coated balls have the same bulk properties, such as elasticity, thermal expansion, and density, of steel, but offer improved surface properties, including chemical inertness, surface hardness, smoothness, and wear resistance as ceramic balls. These surface properties decrease the surface-lubricant chemical reactions during asperity interactions when a PFPE is used [1].

The improved surface roughness of TiC coated balls decreases the ball-race composite surface roughness approximately 35% (assuming TiC R_A of 0.28 µm and 440C R_A of 1.0 µm), allowing an EHL film to form at lower speeds. Fewer asperity interactions occur and when they do occur, there is a decreased tendency for micro-welding and therefore negligible material transfer and surface roughening [2].

Recently, Jones et. al [3] used a bearing simulator and Krytox 143AC, a branched perfluoropolyether (PFPE), to demonstrate enhanced lifetimes of Krytox 143AC using TiC coated balls compared to conventional 440C stainless steel balls. The enhancement was considered to be the result of decreased reactivity between the TiC surface and the PFPE. In the same study [3], the effect of varying Hertzian stress on lubricant lifetime was studied for both steel and TiC coated balls. Increasing the mean stress from 0.75 GPa to 2.0 GPa resulted in an exponential decrease in lubricant lifetime for both material combinations.

The properties of TiC coated balls [4-6] and their improved performance in boundary lubricated rolling contacts have been reported [7-8]. Substantial improvements have been realized by substituting TiC coated balls for uncoated 440C balls when lubricated with PFPEs. The lifetime improvements have been credited to the ability of the TiC coating to retard the chemical degradation of the fluorinated lubricant.

Pennzane is a multiply alkylated cyclopentane synthetic hydrocarbon with desirable lubricant qualities for space applications, including viscosity, pour point, and vapor pressure. A six-year life test of a CERES bearing assembly using Pennzane yielded excellent results [10]. Tests conducted at Lockheed Martin compared Pennzane 2001A to Bray 815Z, a standard space lubricant, and showed Pennzane to have at least a five times life advantage over Bray 815Z [11] in oscillating bearing tests operating in boundary lubricated conditions.

The objective of this study was to determine if there was a benefit with using TiC coated balls with another common space lubricant, Pennzane 2001A, under boundary lubrication conditions. Also, the effect of increasing the mean Hertzian stresses (1.0, 1.5, and 2.0 GPa) on lubricant lifetime was studied using a vacuum Spiral Orbit Tribometer (SOT). Other conditions included: ~210 RPM, ~50 mg lubricant, room temperature (23°C), and an initial vacuum of <1.3 x 10^{-6} Pa.

EXPERIMENTAL

The NASA Spiral Orbit Rolling Contact Tribometer (SOT) was used for all tests and is shown in Figures 1 and 2. The SOT is used for accelerated life testing in ultrahigh vacuum and simulates an angular contact bearing both in operating stress level and rolling motion.

The tribometer is essentially a thrust bearing: a single 12.7 mm diameter ball sandwiched between two flat, 50.8 mm diameter disks, which simulate bearing raceways. The lower disk is held fixed and the top disk is rotated. During rotation, the ball moves in a spiral orbit that is related to the frictional force between the ball and disks. The guide plate (see Figure 2) is used to return the ball to its original orbit once per revolution. The force the ball exerts on the guide plate is measured and can be related to the friction force. This tribometer is further described in References 9 to 12. Other details of the tribometer and its previous usage appear in References 3, and 13-15.

Accelerated testing is achieved by using small amounts (~50 µg) of lubricant. During the test, the lubricant is continuously consumed and eventually the absence of lubricant results in increased friction. Test failure was defined when the friction exceeded 0.28.

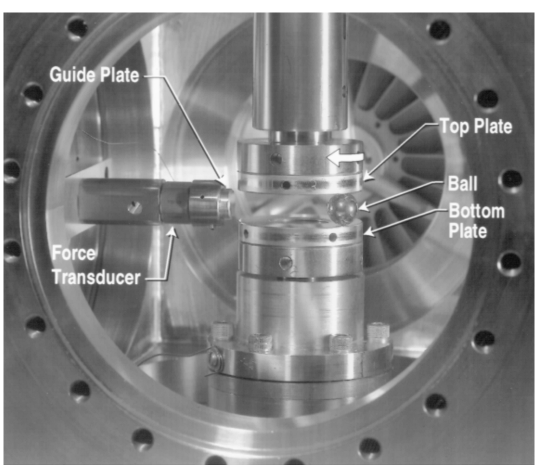

Figure 1 – The Spiral Orbit Tribometer

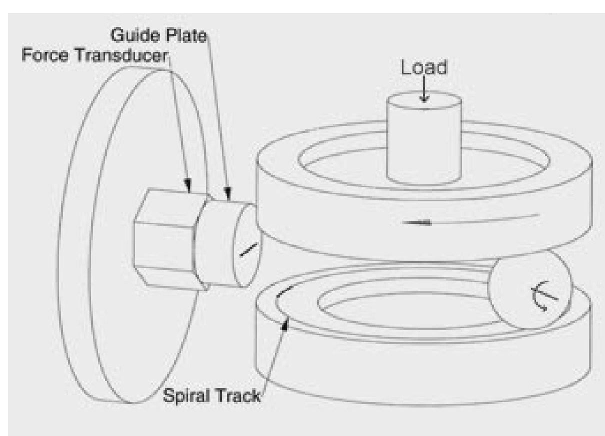

Figure 2 – The spiral orbit tribometer (SOT)

For these tests, the guide plate and disks were made from hardened (R_c~59) 440C stainless steel. The ball was either grade 25, 440C stainless steel or CSEM TiC coated 440C stainless steel. The guide plate and disks were polished to an average surface roughness (R_a) of 0.05 μm.

The disks, ball, and guide plate were sequentially placed in an ultrasonic bath for five minutes using each of the following solvents: hexane, methanol, and distilled water. They were then rinsed ultrasonically for one more minute in methanol, dried with nitrogen, and placed into a UV-ozone box for fifteen minutes [16] to remove residual carbonaceous residue. The ball was rotated every five minutes to ensure that the entire surface had been treated. The samples were removed, the ball was lubricated, and the parts placed in the vacuum system. The experiment was automatically started after the vacuum level dropped below 1.3×10^{-6} Pa. Tests were performed using both 440C and TiC coated balls, mean Hertzian stress levels of 1.0, 1.5, and 2.0 GPa, and a top plate rotational speed of 210 RPM. Friction force and pressure were constantly monitored and the test was terminated when a friction coefficient of 0.28 was exceeded.

RESULTS

The effect of mean Hertzian contact stress and TiC coated balls on lubricant lifetime is shown in Figure 3. Normalized lifetime is calculated by dividing the number of ball orbits to failure by the lubricant charge, yielding orbits/μg. Four tests were run at each condition and the lifetimes averaged. A decrease in lubricant lifetime that is apparently exponential as a function of contact stress is evident for both the 440C ball and the TiC coated ball. This correlation was also observed by Jones et. al [3] using Krytox 143AC. The TiC coating does not have an effect on lifetime relative to the uncoated ball using Pennzane 2001A.

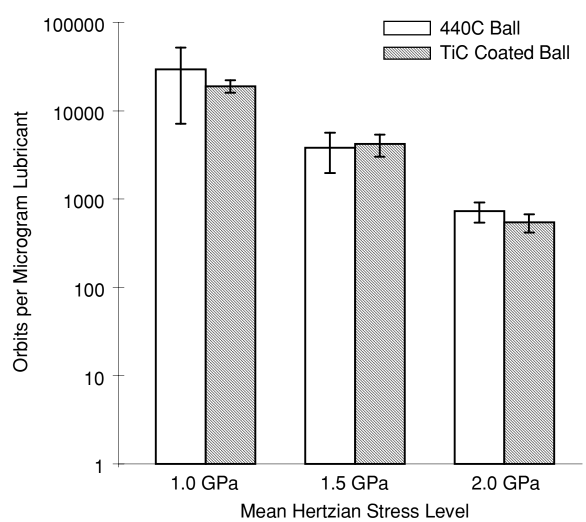

Figure 3 – Effect of Hertzian stress on lubricant lifetimes using 440C and TiC coated bearing balls (Pennzane 2001A)

The Pennzane life tests did show significant improvement over Krytox 143AC [3] with both material combinations. These results correlate well with actual bearing tests (max Hertzian Stress of 1.1 GPa) being performed at Lockheed-Martin as shown in Figure 4 [11] using 440C bearings. These tests were designed to study the effects of different solvent cleaners on bearing lifetime.

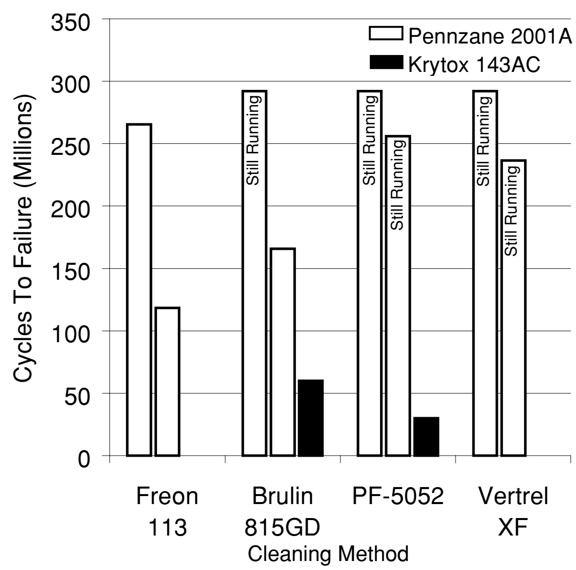

Figure 4 – Bearing data from Lockheed-Martin showing much longer lifetimes with Pennzane 2001A when compared to Krytox 143AC

DISCUSSION

In the spiral orbit tribometer, most of the orbit represents normal rolling with pivot [9], which is observed in instrument bearings. When the spiraling ball contacts the guide plate, termed the scrub, pure sliding takes place between the ball and upper plate.

Energy dissipation is the driving force behind lubricant degradation. In the SOT, energy is dissipated in the Hertzian contact due to pivoting during rolling and sliding during contact with the guide plate [9]. Severity is defined as the total energy dissipation per unit time and a detailed analysis of energy loss during rolling/sliding in a three-ball system can be found in Reference 9. The same analysis can be applied to the one ball system.

Severity can be integrated over the complete ball orbit taking into account the fraction of the ball's surface rolled upon per orbit. It is assumed that the lubricant lifetime is inversely proportional to the energy dissipated and it is possible to calculate the lifetime at different stress levels [3]. Figure 5 shows the results for these tests plotted as a function of load, normalized to their lifetime at 2.0 GPa. There is good agreement between the theoretical calculations and the experimental data. This trend was also observed in the SOT by Jones et al. [3]. Therefore, the lifetime dependence on load can be understood on the basis of lubricant degradation by frictional energy dissipation at the ball/plate contacts.

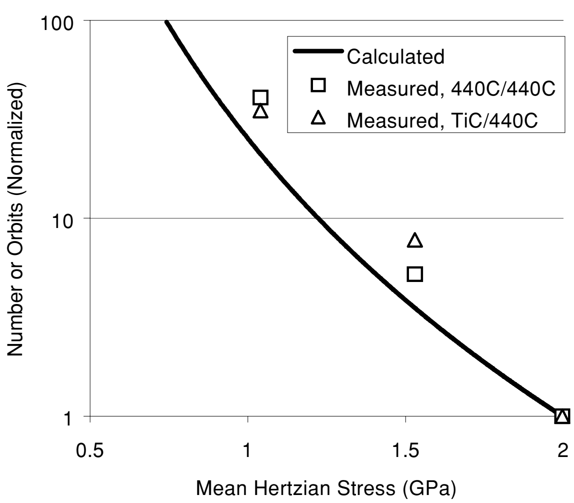

Figure 5 – Relative lifetime of Pennzane 2001A as a function of load normalized to the lifetime at 2.0 GPa in the SOT tribometer

X-ray photoelectron (XPS) analysis was performed on both the coated and non-coated balls after the test concluded. The analysis reveled iron on the surface of the TiC ball. To determine if the iron was transferred during the last few cycles of the test when most of the lubricant had degraded, a half-life test was performed. A lubricated TiC ball was run to approximately half of the estimated life, removed, and XPS analysis performed. Iron was also present on the surface. This may be the reason there is no observed improvement in lifetime using TiC coated balls in these tests.

Although the TiC coated balls did not increase lifetime under the conditions of these tests, it should be noted that the improved surface characteristics and corresponding lower composite surface roughness gained with TiC balls will allow transition from mixed to EHL conditions at lower speeds.

CONCLUSIONS

1. No enhancement in Pennzane 2001A lubricant lifetime under boundary lubrication conditions was observed when substituting 440C balls with TiC coated 440C balls
2. There is an exponential decrease in lubricated lifetime of Pennzane 2001A with increasing contact stress level
3. Relative lubricant lifetime can be correlated with the severity of energy dissipation in the rolling/sliding contacts

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